Rand Corp.
(NASA Contract NASR-21(05))

39 p. ref Prepared for Proc. of Conf. on Artificial Satellites, Blacksburg, Va., 12-16 Aug. 1963

UNPUBLISHED PRELIMINARY DATA

N64 11740 *
CODE-1
(NASA CR 52904; P-2801)

OTS

GEOMAGNETISM AND THE IONOSPHERE

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Oct. ~~October~~ 1963

[9] conf

OTS PRICE

XEROX $ 3.60 ph

MICROFILM $ 1.37 mf.

P-2801

I. Introduction

Near the earth, many natural processes appear to be dominated by the geomagnetic field. In recent years, discoveries and observations made by artificial satellites and space probes have greatly extended our knowledge of these processes. The proliferation of such observations has in fact greatly strained our ability to interpret phenomena in the light of theory. This situation is by no means a new one in geomagnetism. For more than half a century, ionospheric research of importance to radio has been closely linked to that of importance to geomagnetism. As early as 1883, Balfour Stewart[1] suggested that ionized regions of the upper atmosphere might be the site of upper air winds blowing to produce varying electric currents, causing changes with time in the geomagnetic field. The possibility that more than one ionized region might be involved arose in the course of the further development of Stewart's dynamo theory of the geomagnetic variations.[2] The cause of the ionized regions was thought to be wave radiation. In addition, contributions of solar charged particles to the ionization at levels near 100 km was discussed by Birkeland[3] in his studies of the auroral-zone electric currents causing geomagnetic bays. He found that these electric currents must, on occasion, exceed 1,000,000 amperes, and hence require a considerable flow of ionized particles within the atmosphere. He also undertook experiments in which he propelled electrons within an evacuated chamber toward a small magnetized <u>terrella</u> simulating the earth magnet. These experiments provided photographs of illuminated features on the <u>terrella</u> and of ring currents at higher levels, which furnished graphic aids of inspirational importance to theoretical workers in geomagnetism and aeronomy over the 60-year period that followed. The concepts introduced by Birkeland, though based upon experiments in plasma physics, were discussed in terms of particle physics. The fluid concept of plasma physics had not yet been brought forward, though flow of electrical and magnetic energy as effluvia down geomagnetic field lines had been postulated in rudimentary form as early as 1693, in discussions of auroras, by

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Abstract

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The geometry of the magnetosphere and the dynamics of energetic particles and plasma trapped within it are discussed in relation to some problems of geomagnetism. Local acceleration of trapped particles is discussed, and the possible origins of electric fields and their roles in this and other magnetospheric phenomena are outlined. It is found that many phenomena of interest may be newly interpreted in terms of a slight extension of the original Chapman--Ferraro theory of geomagnetic storms.

AUTHOR

Acknowledgments

It is a pleasure to record our indebtedness to Drs. Louis Henrich, and E. C. Ray in connection with this work.

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This paper was prepared for the Proceedings of the Conference on Artificial Satellites, held August 12--16, 1963 at Virginia Polytechnic Institute, Blacksburg, Virginia.

Halley and others. It is therefore clear that some early studies in geomagnetism provided fundamental contributions to ionospheric research. Since some geomagnetic time variations arise from varying currents flowing in the ionosphere, and are dynamic manifestations of the ionosphere in motion, measurements of the geomagnetic variations supplement the information obtained from ionospheric soundings. Of course, most of our knowledge of the ionosphere has come from the exploration of the ionosphere by means of radio waves, propagated both upwards from the ground and downward from earth satellites moving above. Ionization has also been measured directly by rocket-borne instruments. The discovery of the Van Allen radiation belts and their subsequent exploration by artificial satellites and space probes added a new dimension to the problems of interest to geomagnetism. The interactions between the ionosphere and trapped energetic particles came to be recognized, and the electromagnetic effects of energetic plasmas imbedded in the geomagnetic field presently play an important role in theoretical studies of geomagnetism and the ionosphere.

It will be the aim of the present paper to summarize and discuss our current understanding of a few selected aspects of geomagnetism. Note is first taken of the solar streams of Chapman and Ferraro[(4)] or of these superposed in time and space, constituting a solar wind.[(5,6)] The interaction of a solar stream with the magnetosphere is next discussed, with special attention to injection and acceleration of solar stream plasma along the nighttime boundary of the magnetosphere. Contributions of hydromagnetic shock waves to the energy of the particles in the magnetosphere are also very briefly noted following Dessler, Hanson and Parker,[(7)] Kern,[(8)] Kellogg,[(9)] and others. The precipitation of particles into high latitudes to produce radio blackouts discussed by Wells,[(10)] Agy,[(11)] Hakura,[(12)] Matsushita,[(13)] and others, is considered together with the auroral and electrojet theories of Martyn,[(14)] Nagata,[(15)] Fukushima,[(16)] Kern,[(17)] Fejer,[(18)] and Swift.[(19)]

Associated motions of the ionosphere, especially the F-region, are noted along with pulsations in the geomagnetic field and conjugate-point phenomena. F-region effects on magnetically quiet days will also be noted with particular reference to the studies of Ratcliffe,[(20)] Hirono and Maeda,[(21)] and others; included will be some remarks on dynamo theories of the E-region. We will discuss early suggestions by Vestine[(22)] and Wulf[(23)] that the dynamo theory or fluid mechanics of the magnetosphere might give rise to magnetic disturbances, through separation of charge by ionospheric motions such as zonal winds, with a consequent generation of electric fields and accelerations of particles in the polar ionosphere. Vestine also suggested that hydromagnetic waves might be propagated within solar streams from sun to earth, eventually producing effects at ground level.[(22)] Some more recent elaborations of this idea are discussed. The hydromagnetic treatment of magnetospheric phenomena is also discussed briefly, following Axford and Hines.[(24)]

II. Geomagnetic and Ionospheric Disturbances Associated with Solar Streams

It is well known that disturbances at ionospheric levels, such as magnetic crochets and solar radio blackouts are often successfully linked to solar flares.[(25)] It is also well known that other ionospheric disturbances, and geomagnetic and auroral effects appear a day or so after a solar flare. This time interval corresponds to the travel times of particles of a few hundred electron volts between the sun and the earth. During great solar flares, protons and other particles with energies approaching tens of billions of electron volts are known to arrive at ionospheric levels. These produce polar radio blackouts, which appear a number of days each year. On occasion, particles presumably of solar origin have penetrated to ground level, even at the equator, where the energy requirements for penetration are extreme. These spectacular effects of high-energy particles, though very interesting, contribute a much smaller total energy than do the large numbers of lower energy particles impinging on the ionosphere. The latter are thought of as having acquired energy in or near the active solar regions in some manner not yet understood. Until recently even low energy particles incident on the atmosphere were thought to come directly from the sun. But the energy fluxes of such low energy particles measured within the terrestrial atmosphere exceeds those expected from the results of space probes outside the magnetosphere; therefore, a mechanism for accelerating particles within the magnetosphere seems necessary. Particles such as those observed over some months by Mariner II in its flight to Venus have travel times of about a day between the sun and the earth, and the particle fluxes resemble (though not in detail) the solar outflows postulated long ago by Chapman and Ferraro.[4]

III. The Chapman-Ferraro Theory

Figure 1 shows an idealized solar-stream consisting of ions and electrons with temperatures of a few tens of electron volts interacting with the geomagnetic field, as imagined by Chapman and Ferraro. The particles in the stream move radially outwards from the sun, and successive faces of the stream are shown. The interaction of a solar stream with the magnetosphere is shown again in Fig. 2. The geomagnetic field and its contents are compressed, and the solar stream passes by on all sides. It was suggested that particles might enter the magnetosphere on the day side at two singular points, one in high northern and the other in high southern latitudes. The figure also shows electric charges distributed on the boundary on the night side. This charge distribution will give rise to an eastward directed electric field. Crossed with the upward directed field lines of the terrestrial dipole (at the equator), such an electric field would drive particles towards the earth and into the magnetosphere and radiation belts. We shall consider this charge distribution later in connection with the results of Explorer XIV for electron fluxes in the nighttime magnetosphere.

Since some magnetic disturbances are measured at ground level every day, streams of varying density and particle energies are probable. Thus, solar streams must be considered as irregular, and their interactions with the magnetosphere are probably nonlinear, even for the initial phase of a storm that was worked out analytically by Chapman and Ferraro. This circumstance has been discussed by Parker,[5] Obayashi,[26] Elliott,[27] Rossi,[28] and others, though without much analytical detail because of the inherent difficulty of the problem. A substantial advance in information that confirmed some details of the early work was provided by the information on interplanetary plasmas and fields obtained aboard Explorer X,[29] and subsequently by Mariner II observations between the earth and Venus, reported by Neugebauer and Snyder.[30] Figure 3 shows a quiet-day pattern of magnetic field lines for a 300 km/sec solar wind.[31] Both the front of a solar stream and any magnetic fields carried radially outward by the stream become spiral in form -- a consequence of the 27-day solar rotation. Consider a single filament A, which we regard as a region of enhanced density in the general plasma flow from the sun. As it overtakes the earth each 27 days, it will increase the compression on the magnetosphere, within which disturbances that resemble one another in some respect will recur every 27 days. A model of this kind will explain recurrence tendencies for ionospheric storms, geomagnetic disturbances, and aurora at roughly 27-day intervals. A possible simple 27-day recurrence of this type near sunspot minimum is shown in Fig. 4 for six solar rotations from September 1943 to February 1944.[32] The large pulse enduring about one hour near midnight, if assumed associated with a density increase such as for A of Fig. 3, would imply a highly persistent and stable feature of the solar wind -- a narrow filament. The advancing face of A at the earth will move with an angular velocity depending on the rate of solar rotation, and the distance r from the sun. If the filament passes the earth within an hour (neglecting time constants of effects due to the stream filament), we can estimate its cross section _d_. Taking the solar rotation period to be 27 days = 648 hours, d = (1/648) x 2π x 1.5 x 10^8 km $\sim$ 1.5 x 10^6 km. This small filament thickness is much less than a mean free path in the interplanetary medium, so that preservation of such a filament would require a remarkably stable structure of the stream.

The arrival at the earth of high-energy particles from great solar flares is often associated with a Forbush decrease in galactic cosmic rays. This decrease appears to be brought about by a change in the distribution of the interplanetary plasma and magnetic field.[27,33]

IV. Magnetosphere Boundary

The calculations of Chapman and Ferraro relating to the boundary of the magnetosphere have been extended by a number of workers,[34,35,36] who used various simplifying assumptions. Figure 5 shows results based on calculations of Spreiter and Briggs[34] for a dipole earth inclined to a solar stream.

Consider the distribution of charge near the boundary of Fig. 2. It arises, according to the Chapman-Ferraro theory of 1933, from the electric field there given by $\underline{E} = - \underline{v}_t \times \underline{B}$, where $\underline{v}_t$ is the component of the solar stream velocity tangent to the boundary and $\underline{B}$ the local magnetic field. It can be shown that $\underline{E}$ depends more upon the velocity of the solar stream than upon the stream density. Chapman and Ferraro also showed that this effect is to be expected under widely different conditions of nonuniformity in field and velocity. More recently they have considered that a deeper penetration by protons than by electrons is expected at the boundary, resulting in a charge separation associated with the component of v normal to the boundary. Near the equatorial plane where the geometry is comparatively simple, the tangential component of the stream leads to a positive charge distribution on the morning side of the cavity, and a distribution of negative charges on the evening side of the cavity. We can regard this arrangement as a huge parallel plate condenser, with a dielectric constant ϵ. The value of ϵ is nonuniform within the cavity, since it is given by $\epsilon = 1 + 4\pi Nmc^2/B^2$ where N is the number density of plasma ions, m the mass of a plasma ion, and B is the magnetic field. The electric field lines within the cavity must be orthogonal to those of the geomagnetic field, due to the high conductivity along B. They will be roughly perpendicular to the plane of the midnight meridian at great distances from the earth on the night side, and directed eastward from the dawn to the evening side. Since B is parallel to the magnetospheric boundary, the electric field must be perpendicular to the boundary. The distribution of the electric field within the magnetosphere will be determined by the dielectric constant. Hence, the electric field will be concentrated in regions of higher ϵ; i.e., in magnetospheric regions where B is smaller, or in regions of higher N.

The electric charge distribution shown tentatively in Fig. 2, will clearly affect charged particles within the magnetosphere, and it may influence the locations and intensities of ionospheric current systems. The distribution of charged particles in the tail of the magnetosphere will depend directly on the configuration of the electric field. Figure 6 shows recent results of Frank, Van Allen, and Macagno[37] on the flux densities of electrons of energy greater than 40 kev observed on Explorer XII and Explorer XIV. Note that there is a dearth of energetic electrons beyond about 8 earth-radii along the central axis of the tail. In the absence of particle sources, the direction of $\underline{E} \times \underline{B}$ drift as inferred from the foregoing and from measurements of $\underline{B}$[38] is likely to be such as to give an earthward velocity E/B, sweeping particles from the central region of the tail. It might also be expected that the contours of equal flux intensity would be stream lines for $\underline{E} \times \underline{B}$ drift along electrostatic equipotentials. The magnetic moments of particles will be conserved during such $\underline{E} \times \underline{B}$ drift, so that as the particles are driven earthward into a stronger magnetic field they are also accelerated. Individual charged particles of low energy would be directed earthward along trajectories that closely approach the earth, whereas the motion of individual particles of higher energy would be dominated by the inhomogeneous magnetic field, and they would travel only part of the way earthward. The more energetic particles might eventually encircle the earth in response to magnetic gradient drift. Continued acceleration by the electric field is then possible if the electric field has a smaller component tangent to drift orbits on the day side than on the night side. As has been often done before, it seems necessary to suppose that plasma somehow crosses the magnetospheric boundary from the solar stream, perhaps due to unstable ripples arising in the boundary far out along the tail.[15] The important Helmholtz instability of a plasma moving in contact with a magnetic field was considered by Northrup,[39] who showed that growing irregularities might occur. Dessler[40] has suggested that the sunward boundary of the magnetosphere is stable. Far out along the nighttime boundary, however, it seems likely that fluctuations in the solar stream should give rise to exponential growth of irregularities in the boundary, much as in the case of auroral curtains and arcs discussed by Kern and Vestine.[41] Disrupted irregularities or flutes might remain inside the rapidly moving boundary of the magnetosphere as plasmoids. Once inside they should stream inward close to the boundary, possibly parallel to the contours of equal electron flux shown in Fig. 6 by Van Allen and his colleagues. An adiabatic heating of such plasmoids by compression (increasing B) will follow. Loss of energy from them will contribute to the ionization of the polar ionosphere, as has been remarked by Hines. Figure 7 shows the polarization of an ion beam in a magnetic field, and provides experimental support for the existence of the original boundary-charge distribution of Chapman and Ferraro.[42]

We can estimate charge densities for the boundary region of the magnetosphere. The polarization electric field is $(1/c)\ \underline{v} \times \underline{B}$ or if $B = 10^{-3}$ emu and the tangential velocity $v = 10^{8}$, the field required is $(1/c) \cdot 10^{4}$ esu or 10^{4} emu. An electric field of about 10^{4} emu/cm across the tail of the magnetosphere will produce motions with velocities of the order of 10^{8} cm/sec, corresponding to the tangential velocity of the solar stream. This field requires a potential difference of Ed across the "condenser." The surface charge density at the boundary, σ, is then $(1/4\pi)\epsilon E$, or $\sigma = (1/4\pi c) \times 10^{4}\epsilon$. If $\epsilon = 1{,}000$, $\sigma \simeq 10^{6}/c$ in esu. This gives the number of charged particles per unit area of the boundary as about $6 \times 10^{4}/\mathrm{cm}^{2}$. This surface charge may be considered distributed over a considerable thickness of boundary. For instance the spiral radius of a proton is about 100 km when B is about 100γ (one gamma = 10^{-5} cgs unit). The polarization electric field could be provided by about 6 x 10^{-3} protons/cm^3 in such a boundary region.

Although, from Explorer XIV observations, Cahill has found some departures in the direction of the earth's field from that of a dipole, the magnitude is closely approximated by a dipole even beyond eight or more earth radii.[38] Thus if E = 10^4 emu, B = 10^{-3}, and we assume 40 kev particles, we have an electric drift of V_E = E/B = 100 km/sec under static conditions, in the direction $\underline{E} \times \underline{B}$. If E varies with the time, a polarization drift $\underline{V}_p = (mc^2/eB^2)\dot{\underline{E}}$ appears parallel to $\underline{E}$. If we imagine $\underline{E}$ to develop in 100 sec, say, $\dot{\underline{E}}$ = 10 emu/sec, and protons would drift parallel to $\underline{E}$ with the speed 10/9580 x $10^{-6} \sim 10^3$ cm/sec, or 10^{-2} km/sec. Electrons drift a negligible amount by comparison.

A curvature drift is opposite in direction for electrons and protons, and for a radius of curvature of field line of about 4 x 10^9 cm gives about 20 km/sec for protons (less for electrons). A magnetic-field gradient drift is about 40 km/sec, and the sign is opposite for protons and electrons. A drift due to gravity is very small -- of order 10^{-5} km/sec, perhaps.

An injected plasmoid will therefore drift rapidly earthward at roughly the tangential velocity of the solar stream negotiating a number of earth radii in a few minutes, and the trajectories of individual particles will show a sensible shift of positive ions to the west and of electrons to the east.

V. Dynamics and Particle Acceleration in the Magnetosphere

Recent observations of the solar wind, made by Mariner II, have failed to show energetic electrons in the quantity required to produce auroras, and insufficient energy fluxes to produce the polar current systems of geomagnetic disturbances.[37] Since measurements were made *en route* to Venus, and therefore survey much of the region near the earth's orbit, it seems necessary to invoke a magnetospheric mechanism that can accelerate a part of the existing charged particles of the exosphere. The alternative possibility of accelerating particles by an atmospheric process has been considered by previous studies, without finding a workable mechanism.[17,43] It has, in fact, been suggested years ago that dynamo effects in the ionosphere might contribute electric fields of interest in this connection.[22,23] In recent years these atmospheric fluid-motion concepts have been applied in considerably greater generality to the whole magnetosphere, assuming energizing to ensue under the influence of the impinging solar wind.[24] The generation of fluid motions by interaction of a solar stream with the magnetosphere, hydrodynamic waves (shock waves) within solar streams flowing from sun to earth, and the hydromagnetic aspects of storms, had in fact been discussed by Vestine in 1954 but left undeveloped.[22] This type of theory really emerged through the detailed studies by Dungey,[44] Piddington,[45] Parker,[46] Dessler and Parker,[47] Cole,[6] and, as has already been noted, in the comprehensive statements of Gold,[48] and Axford and Hines.[24] Even earlier, the fundamental concept of magnetic fields frozen into plasma seems to have arisen from storm theory in works of Ferraro, and later by Alfvén. Because of extreme analytical difficulties, many of the various suggestions cannot readily be tested by specific and detailed calculations as was done for the initial phase of storms by Chapman and Ferraro. Accordingly, it appears likely that major clarifications of the magnetosphere--ionosphere interactions will follow rocket, satellite and space-probe measurements of particle fluxes, fields, and composition of the upper atmosphere and magnetosphere.

There have been recent suggestions regarding the acceleration of particles, using concepts of fluid mechanics. One of the more interesting approaches is that of accelerating charged particles by hydromagnetic shock waves within the magnetosphere.[7,8,23,42-51] There is today some uncertainty respecting the role of shock waves in producing more than the sudden commencement of storms, because the various space probes have not discovered sufficiently accentuated wave fronts of potential shock waves inside the magnetosphere. However, the description of the sudden commencement as a hydromagnetic shock wave remains cogent.[4,47,48,50,51]

The processes of acceleration actually operative are of considerable interest to radio workers, because particles are presumably dumped from above and into the ionosphere. According to Kern,[17] the interaction of a solar stream with the magnetosphere may give rise to nonequilibrium distributions of energetic trapped particles so that electrons and ions separate (due to gradient and curvature drifts in the nonuniform magnetic field). Such charge separation in the trapped radiation gives rise to electric fields in auroral regions. As shown in Fig. 8, these drive the electrojets of bays and cause dumping of trapped particles that produce radio blackouts in high latitudes such as those described by Wells[10] and others. These points have also been discussed by Fejer,[18] and by Cole[6] in criticism of Piddington's series of papers on storms.

The resulting electric fields in the E-region of the northern hemisphere will necessarily have a conjugate pattern in the southern hemisphere. The driving emf's, whether north-south or otherwise, must act across a segment of the ionosphere as shown in Fig. 9, due to Fejer.[18] We see that the electric driving forces produce conjugate electrojets at both auroral zones, a point noted earlier by Kern and Vestine.[41] Since mirror-point heights usually differ above conjugate northern and southern points joined by a geomagnetic field line, aurora may appear at one station and not at its conjugate. Also the electric conductivities may differ in the two hemispheres, so that a weak bay in one hemisphere may be accompanied by a strong bay in the other. In the same way, radio blackouts may appear strongly in the hemisphere where mirror points are low near the electrojet, and not at all in the other hemisphere where mirror-point heights are more elevated above ground level. This situation also applies to the flux-tube dynamics of Axford and Hines, and should be considered in discussing the effects of interchange motions in the magnetosphere.

Various suggestions have appeared suggesting that electric fields assist in loading new particles into the Van Allen radiation belts, e.g., see Vestine[52] or Akasofu and Chapman.[51] In fact, in at least one theory of magnetic storms due to Alfvén,[53] it is shown that many details of magnetospheric phenomena can be explained by using electric fields. Alfven imagined that motion of solar streams across the solar magnetic field gave rise to the requisite electric fields in the vicinity of the earth. In the foregoing discussion on the results of Explorer XIV, we have also noted the possibility of a broad scale electric field, based on Chapman and Ferraro's calculations of the charge distribution at the magnetospheric boundary.

A few comments relating plasma flow to electric charges on the magnetosphere boundary seem appropriate. Axford and Hines[24] note that the fundamental equation governing the motion of a low energy plasma in the magnetosphere is $\underline{E} + \underline{V} \times B = 0$, where losses and conduction in the ionosphere are neglected. We can derive $\underline{E}$ from a knowledge of $\underline{V}$ and $\underline{B}$ in a hydromagnetic medium. The only quantity known in even its grosser aspects is the main-field dominated term $\underline{B}$, and as Fejer has remarked,[18] in the outer magnetosphere $\underline{B}$ is dominated by the presence of currents in the boundary and hence becomes difficult to include in a quantitative theory. It is clear that the boundary conditions for the charge yielding $\underline{E}$ are uncertain. The charge distribution described in III seems able to supply a distribution of electrons resembling that of Van Allen and his colleagues. But the electron flux distribution could, in principle, be supplied by other charge distributions. For example, the Axford and Hines circulation shown in Fig. 10 can be adopted and the charge distribution driving it can be inferred. This in general yields excess charge inside the magnetosphere, and also requires consideration of the nonuniform dielectric constant of the medium and the distorted configuration of the magnetic field $\underline{B}$.

From the Chapman-Ferraro charge distribution, we can construct an oversimplified model of the supply of particles with plasma driven forward from far along the tail of the magnetosphere. This flow forward constitutes the primary part of our "circulation" scheme, but return flow, unless outside the magnetosphere (which would require modifying the boundary conditions), is not permitted. Thus the plasma must be either dumped or its energy dissipated within the magnetosphere. This picture contrasts strongly with the Axford-Hines circulation pattern for motions in the magnetosphere (Fig. 10).

VI. Conjugate Point and Other Ionospheric Disturbance Phenomena

The time changes of the F-region and E-region during geomagnetic disturbance are of considerable interest in radio-physics because of their importance in radio communications. It has only recently come to be realized that low energy electrons in the upper F-region probably interchange between hemispheres along geomagnetic field lines. This means that equatorial anomalies in the F-region require interpretation in terms of conjugate point locations, a matter recently discussed in a critical review address by Ratcliffe.[20] A convenient chart of conjugate points given recently by Kern and Vestine[41] is presented in Figs. 11A and B. Some features of similarity as well as dissimilarity in correlations of northern and southern hemisphere stations with solar indices have been noted by Mariani,[54] using noon values of f_oF_2 for two eleven-year periods, 1937-1947, and 1947-1957. For latitudes above 55°N or S maxima appear in linear regression coefficients connecting number density in the F_2-region with solar parameters. There are also indications of a strong number-density dependence in the annual means of f_oF_2 for nearly conjugate stations in the region 30N to 30S. Mariani attributes these effects to dumping of radiation-belt electrons with energies in excess of 40 kev and fluxes of 10^5 to $10^6/\mathrm{cm}^2\mathrm{sec}$ (energy fluxes 10^{-4} to 10^{-3} erg/cm^2). His estimates are based on the measurements of low energy electron flux by O'Brien[55,56] and Krasovskii, et al.[57] Mariani does not discuss mechanisms of dumping the particles. However, the local acceleration of trapped particles in the magnetosphere is implied by such dumping. This has been indicated previously by O'Brien,[55,56] Vestine,[58] Chamberlain, Kern, and Vestine,[59] and Vestine and Kern.[60] Due to the constancy of a particle's magnetic moment $\mu = (1/2)m\, v_1^2/B$, where m is the mass of the particle, and $v_\perp$ its spiral velocity, the mirror field B_m depends on the total kinetic energy of a particle. An increase in the velocity of the particle due to some acceleration mechanism means B_m must increase, hence involves a lowering of the mirror point, and a possible dumping of particles. Particles supplied to the radiation belts by the Chapman-Ferraro electric field across the tail of the earth are locally accelerated by $\underline{E} \times \underline{B}$ drift into a stronger magnetic field. The lowering of mirror points due to local acceleration may also be discussed using the second (or longitudinal) adiabatic invariant,[59] and other features of their dynamics can be clarified.

The various phenomena associated by Mariani[54] with the dumping of particles are probably modulated by regular seasonal changes in the orientation of the geomagnetic field with respect to the solar wind as shown in Fig. 5. A direct effect on averages of the annual magnetic variation is apparent in Fig. 12. Season dependent changes in the F-region have been noted.[61] An interesting seasonal variation appears in whistlers.[62] There is also a seasonal effect on the polar-cap distributions of S_q electric currents (Fig. 13), as noted by Nagata.[63] Some of these effects may be related to the seasonal variation on the distribution of a broad-scale electric field within the magnetosphere.

A number of conjugate-point effects involving rapid transient changes or pulsations in the geomagnetic field are associated with the appearance of ionospheric changes, or with aurora. Thus, Harang[64] found regular magnetic pulsations of some minutes period accompanying radio signals returned from the ionosphere. It was noted quite early that pulsations of auroral illumination on occasion have the same period as geomagnetic pulsations. Vestine found intervals of 2-second pulsations by direct timing of an auroral display that lasted nearly an hour in 1933.[65] In recent years these phenomena have been explored extensively and good correlations have been established between magnetically conjugate stations by

Campbell and Leinbach,[66] Troitskaya, et al.,[67] and by Campbell and Matsushita.[68] Geomagnetic pulsations in field noted by a magnetometer aboard Explorer X were also discussed by Ness, et al.,[69] and a number of writers have presented hydromagnetic theories of such pulsations.[70,71]

Ionospheric effects have also been discussed using models of solar-cycle variations in the upper atmosphere.[72,73] There are also effects due to storms such as those observed by Jacchia[73] and Paetzold and Zschoerner.[74]

An extensive series of papers dealing with general aspects of ionospheric storms in the F-region has appeared.[63,75-78,79-85] These results will not be considered in detail here. There is, in general, considerable temporal agreement between effects noted in the F-region and those in geomagnetic storms. Up to a height of about 200 km, the storm effects are less pronounced. In the F-region a thickening occurs on the first day of a storm, and there is often loss of ionization later, perhaps due to ionospheric heating.

A recent review of some storm effects in the F-region has been given by Somayajulu.[85] He dealt especially with effects noted during three severe magnetic storms. An interesting feature was the noontime depression in the height of the F2 maximum of about 100 km at Washington, D. C., on the storm days as compared with quiet days; other changes are indicated in Fig. 14. For 42 storms, Matsushita[83] studied average aspects of the electron density N, the total ion content in a vertical column of unit area, and the electron content below various heights of the ionosphere. He analyzed these data according to storm time and SD variations at 8 stations. Electron-density profiles on both storm and magnetically-quiet days were plotted against height and latitude. For the SD variations, most of the results in middle latitudes seem explicable in terms of electric fields of polar electrojets, operating on the ionosphere in combination with the geomagnetic field. For the storm-time variation, Matsushita found an apparent increase in ionization occurring above the maximum height of the F-region at the beginning of the main phases of storms. He suggests that this ionization may diffuse down the magnetic field lines and, under influence of gravity and pressure gradients, move to regions above low-latitude stations. In slightly higher latitudes a rapid decay process associated with temperature increases in the upper F-region in summer may occur.[20,84]

The final figure (Fig. 15), showing variations in phase height of 16 kc/sec waves, has been discussed by Ratcliffe and Weekes.[84] The effects shown have been interpreted in terms of change in D-region height. The figure also shows that during storms and during the after field of storms there are nighttime changes of special interest.

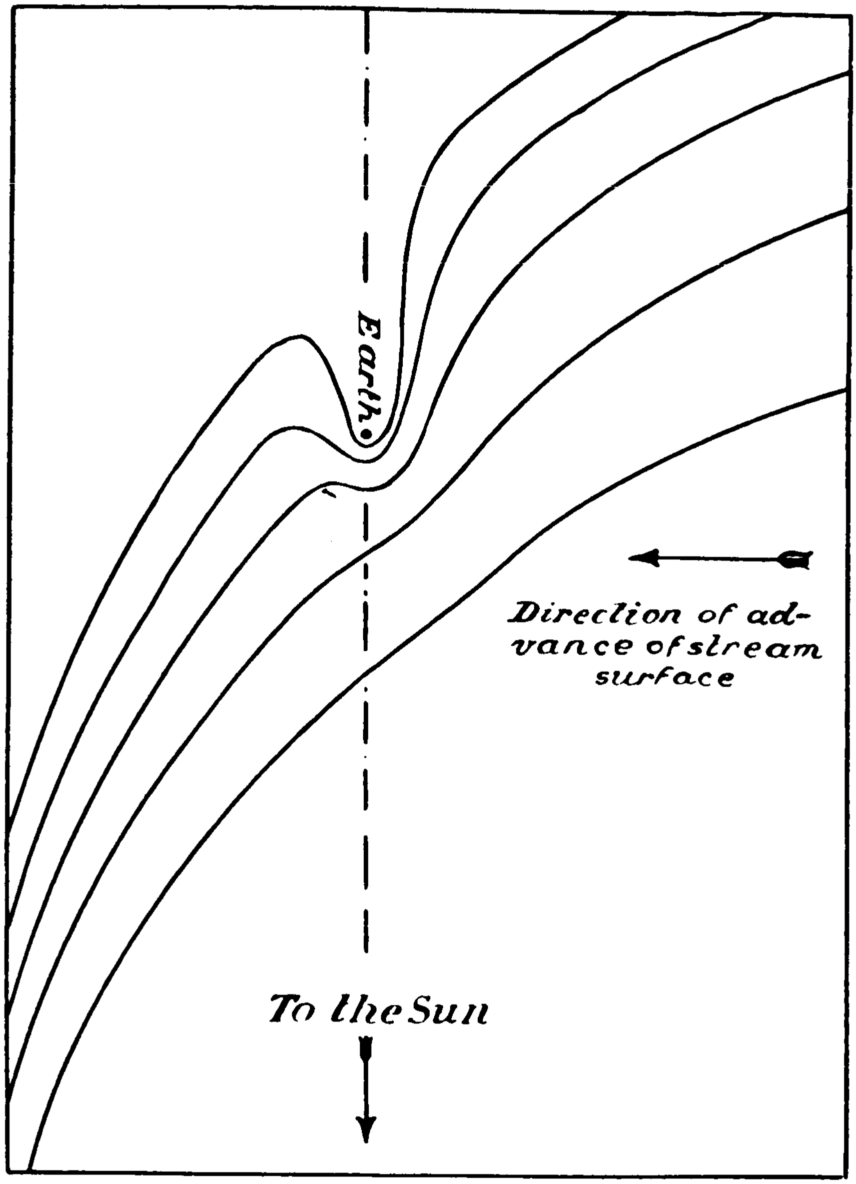


Fig. 1 Successive equatorial sections of the surface of advancing stream (after Chapman and Ferraro)

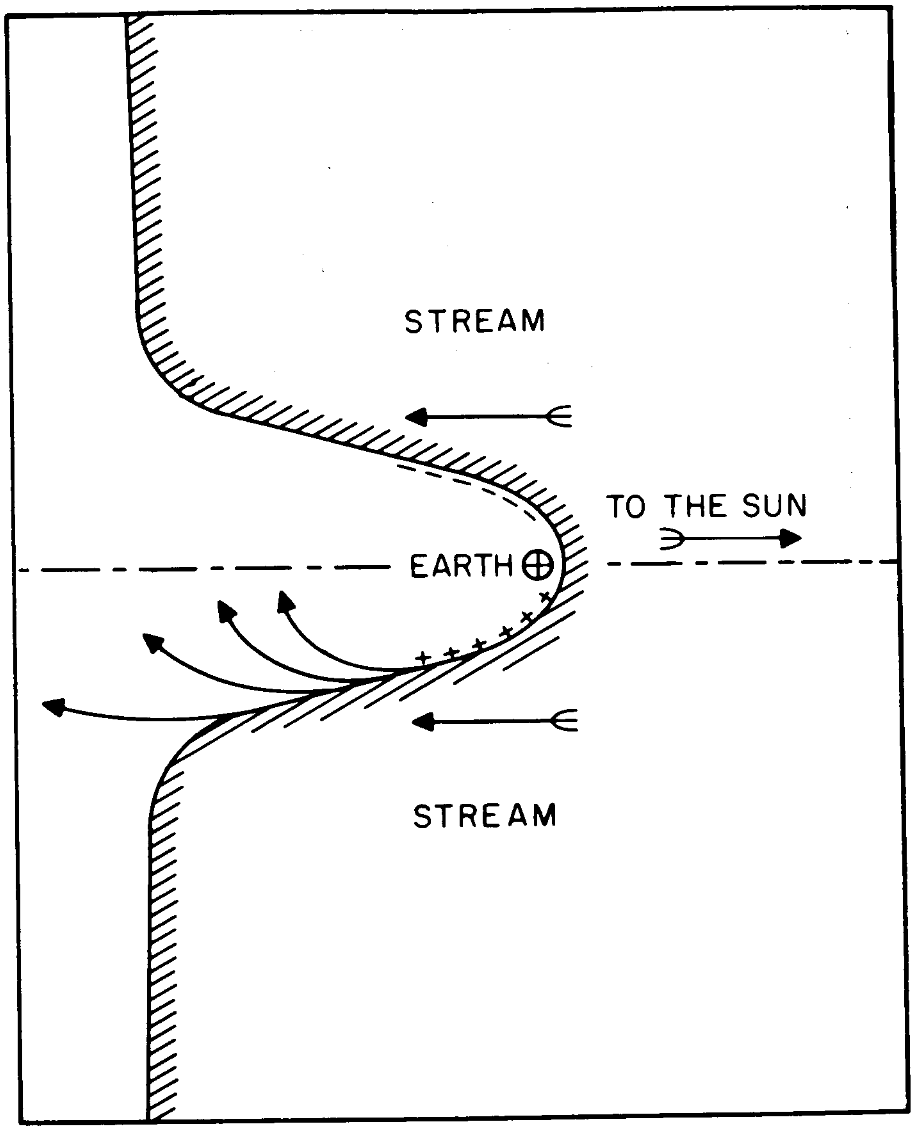


Fig. 2 Equatorial section of magnetospheric boundary (after Chapman and Ferraro)

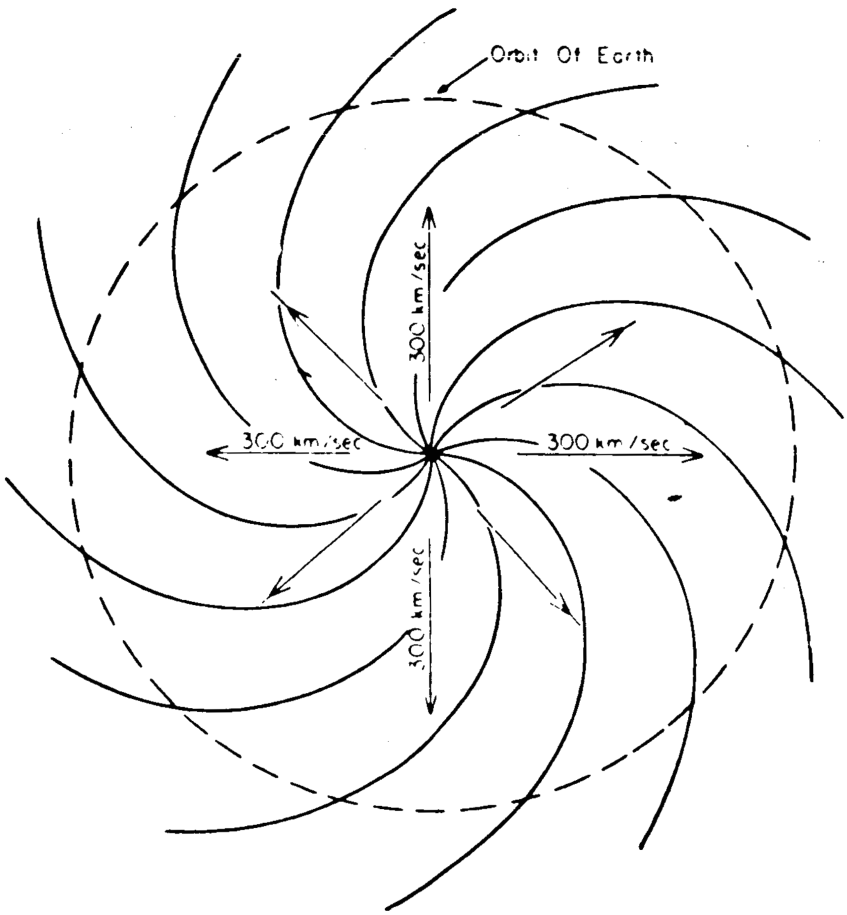


Fig. 3 Extension of the general solar field by an idealized uniform quiet-day solar wind of 300 km/sec in the solar equatorial plane (after Parker)

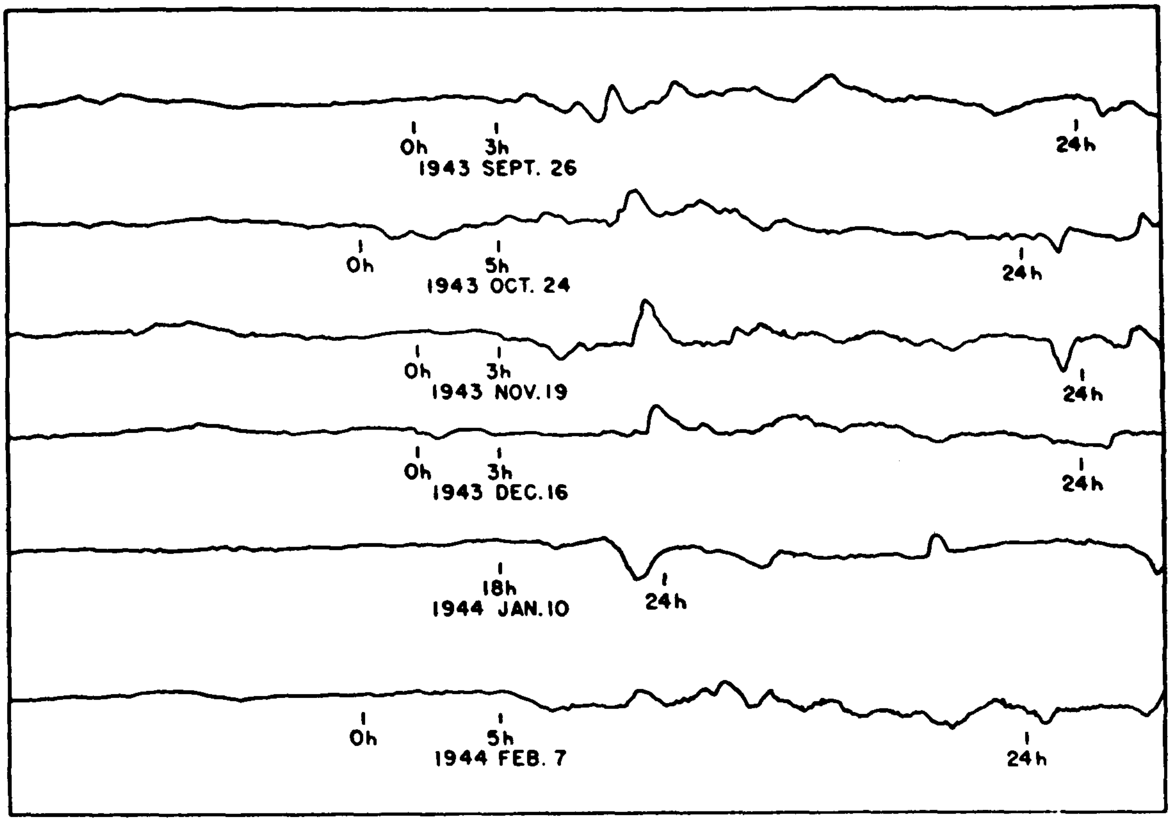


Fig. 4 Tracings from the records of the horizontal component of the earth's magnetic field recorded at Mount Wilson, showing portions at the time of six abrupt onsets (after Wulf and Nicholson)

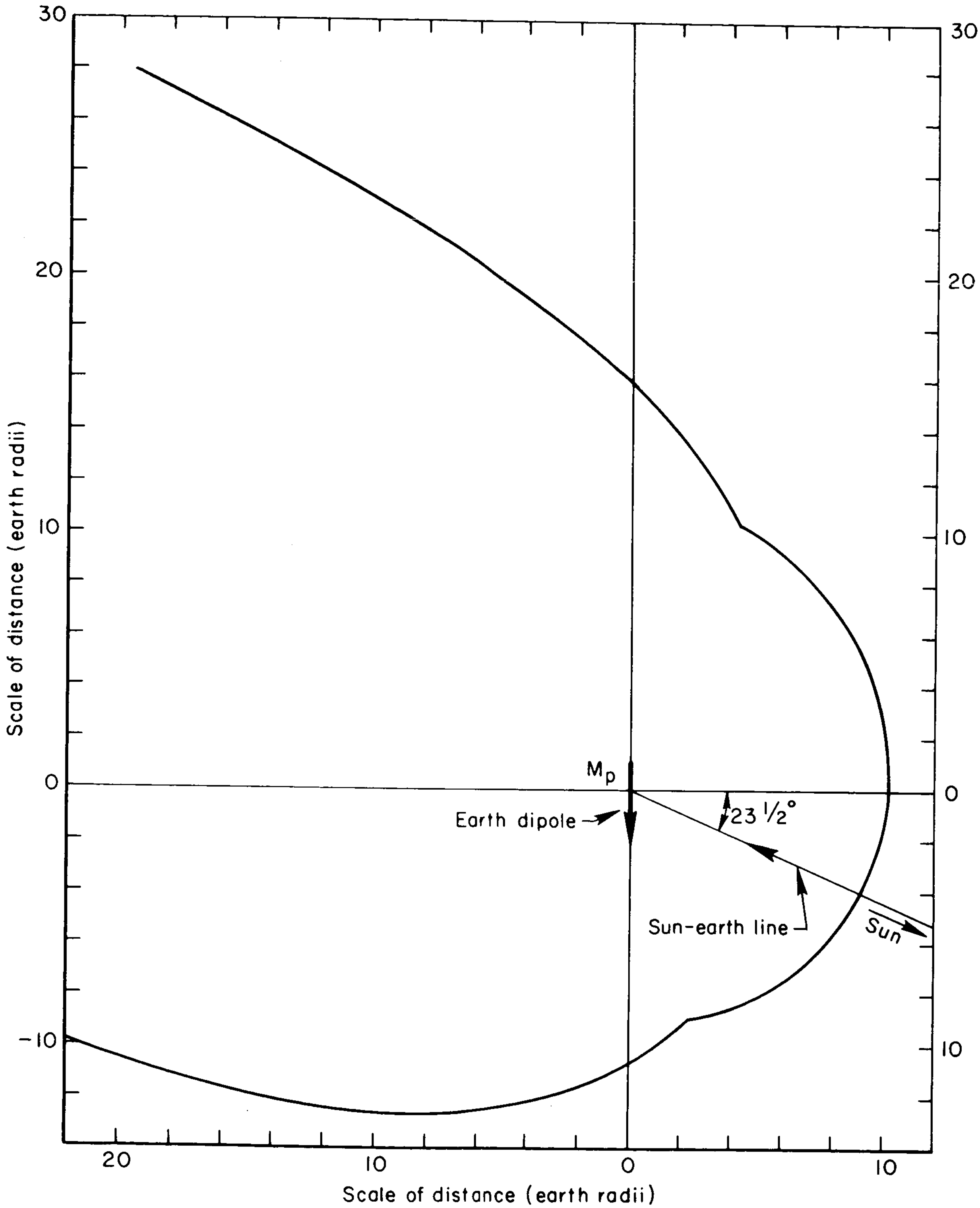


Fig. 5 Form of boundary of magnetosphere in the meridian plane containing dipole axis and sun-earth line, winter solstice

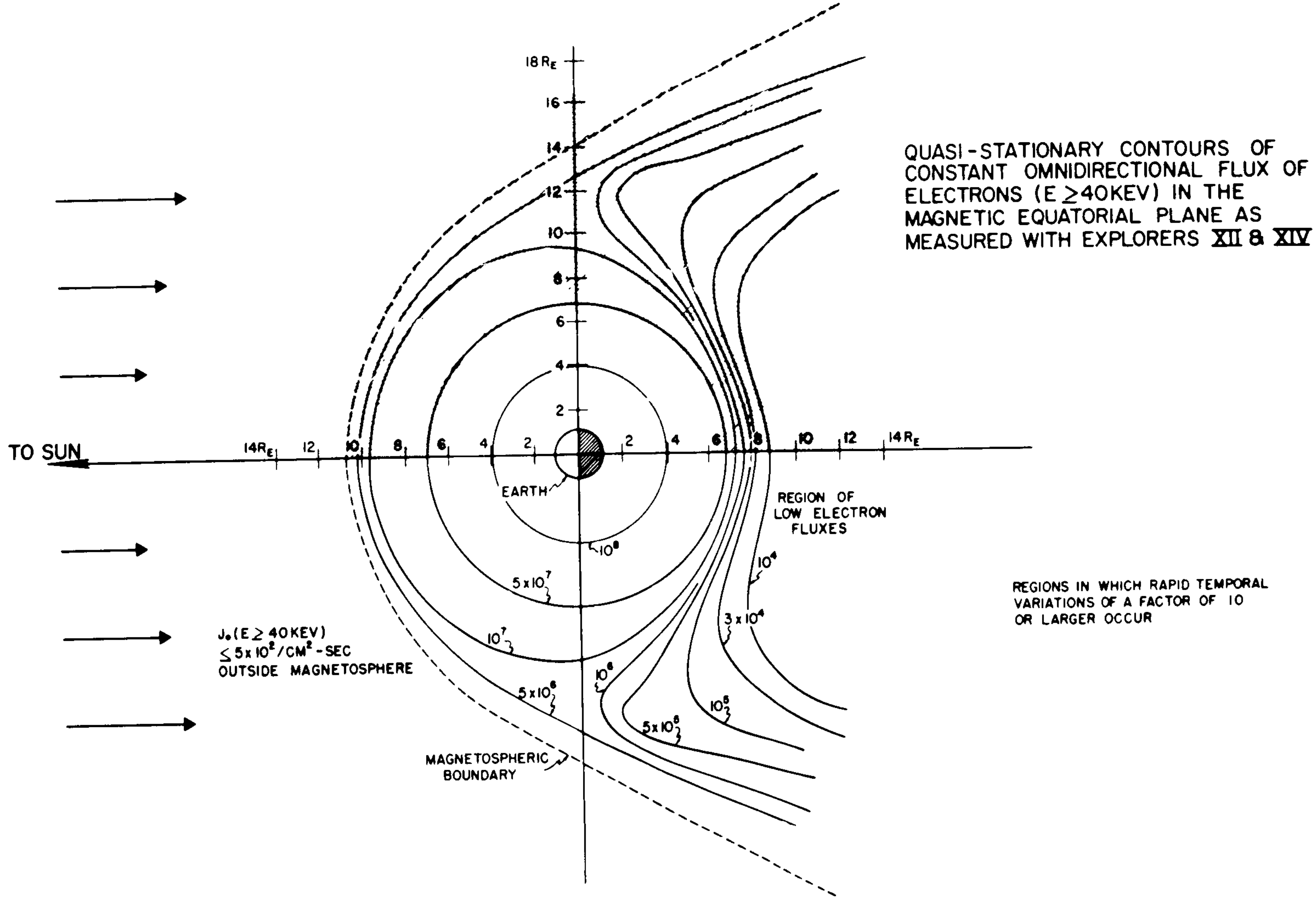


Fig. 6 Quasi-stationary contours of constant omnidirectional flux of electrons (E ≥ 40 Kev) in the magnetic equatorial plane as measured with Explorers XII and XIV (after Frank, Van Allen, and Macagno)

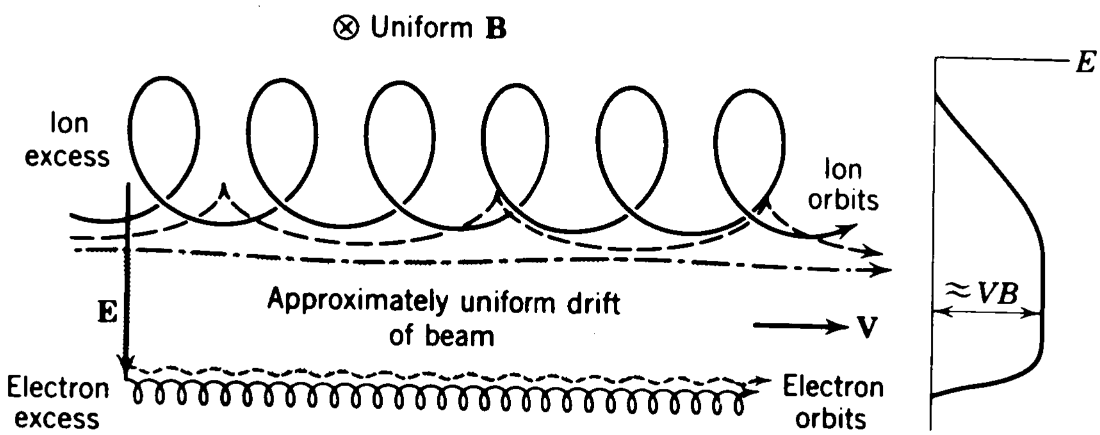


Fig. 7 Schematic representation of typical particle orbits and magnitude of electric field in a dense beam of ions and electrons crossing a magnetic induction B. The beam is assumed to be thick in the B-direction. (after Rose and Clark)

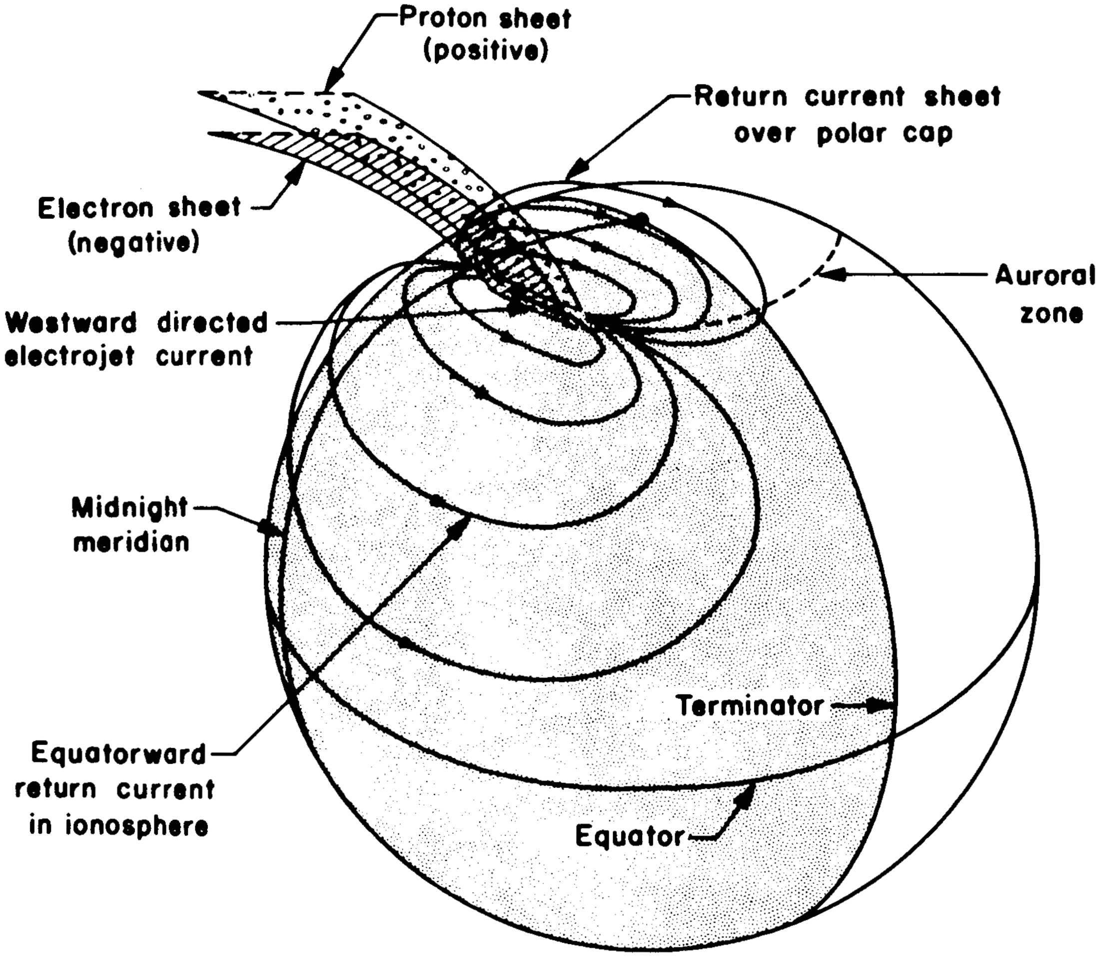


Fig. 8 Polarization of radiation incident in the auroral zone and Hall conduction polar-electrojet currents (after Kern)

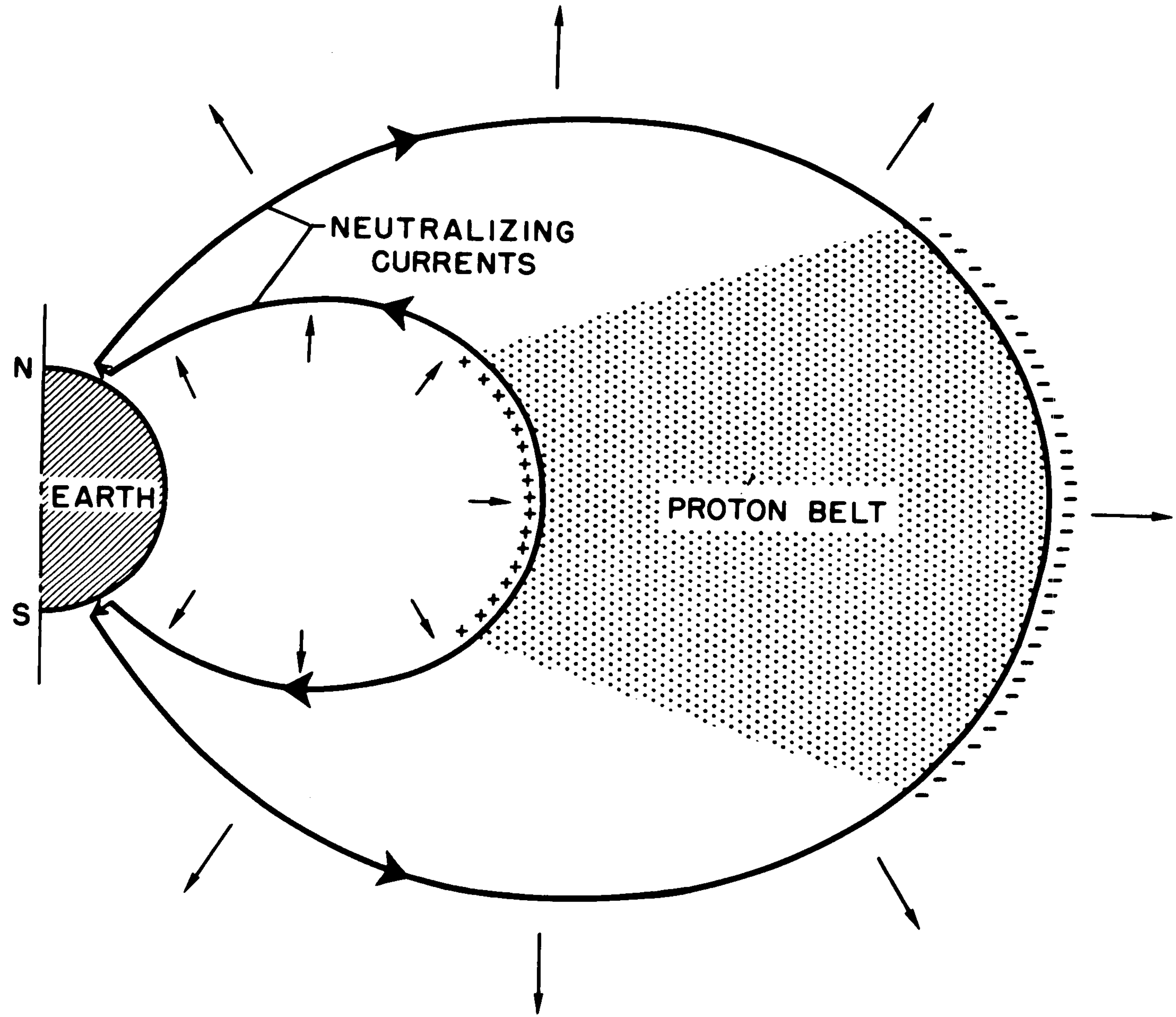


Fig. 9 Current and electric fields in magnetosphere during magnetic bay (after Fejer)

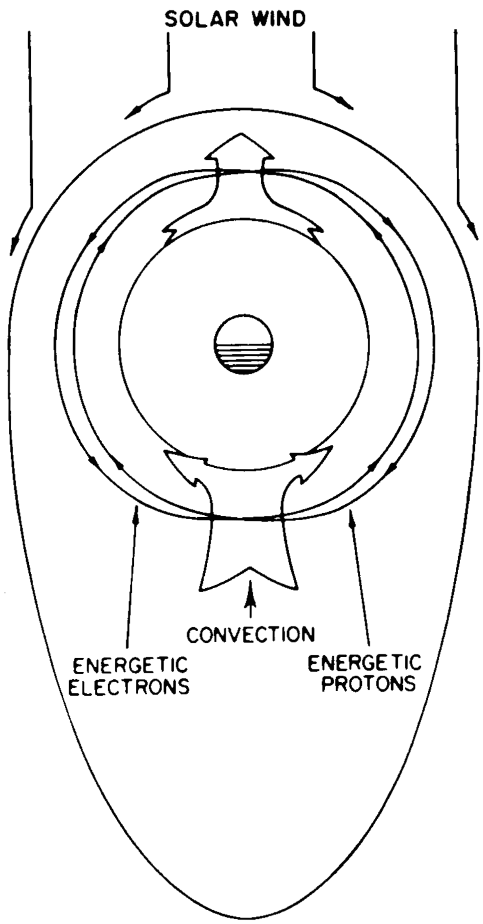
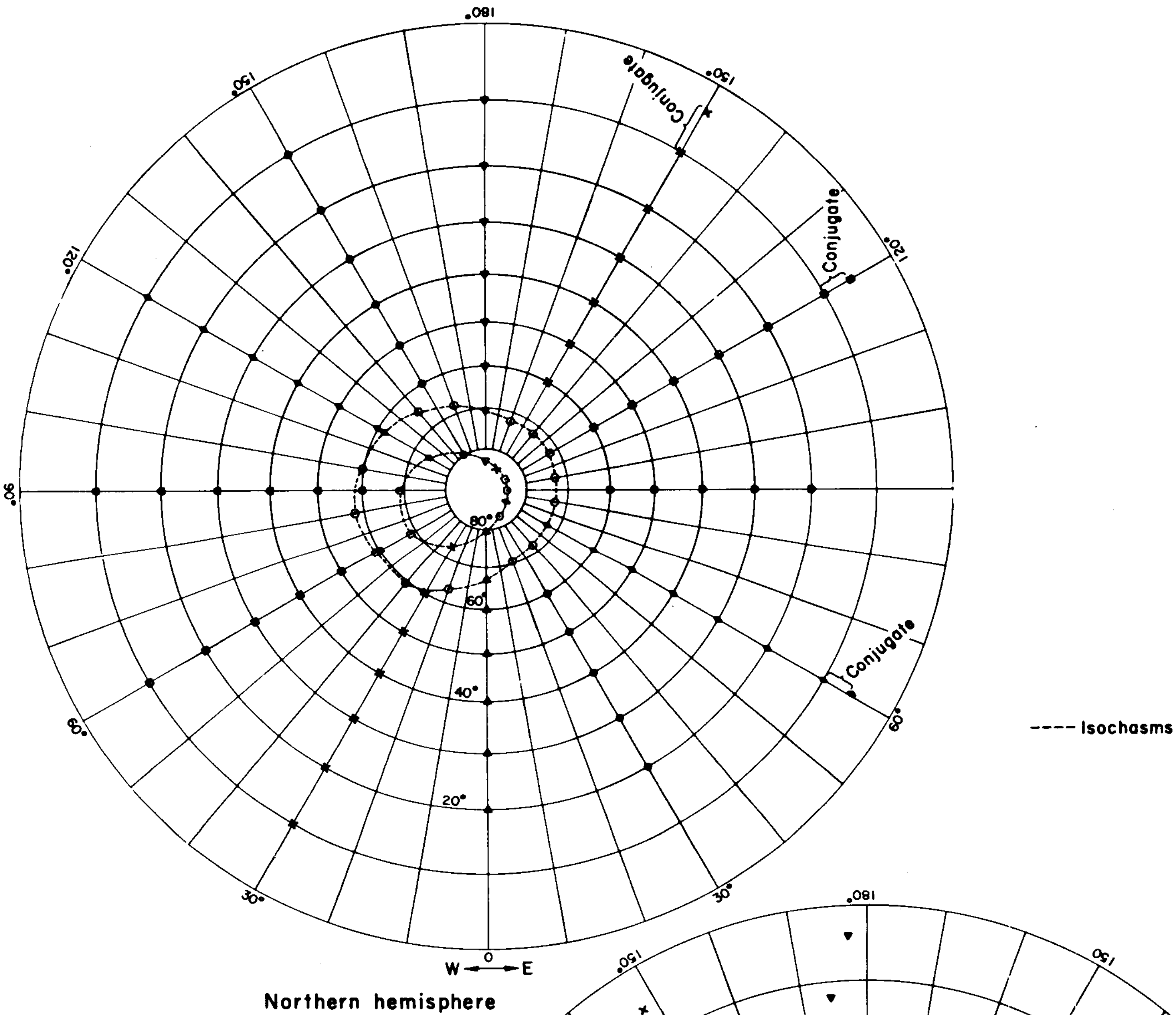


Fig. 10 Theoretical circulation of the magnetosphere (after Axford and Hines)



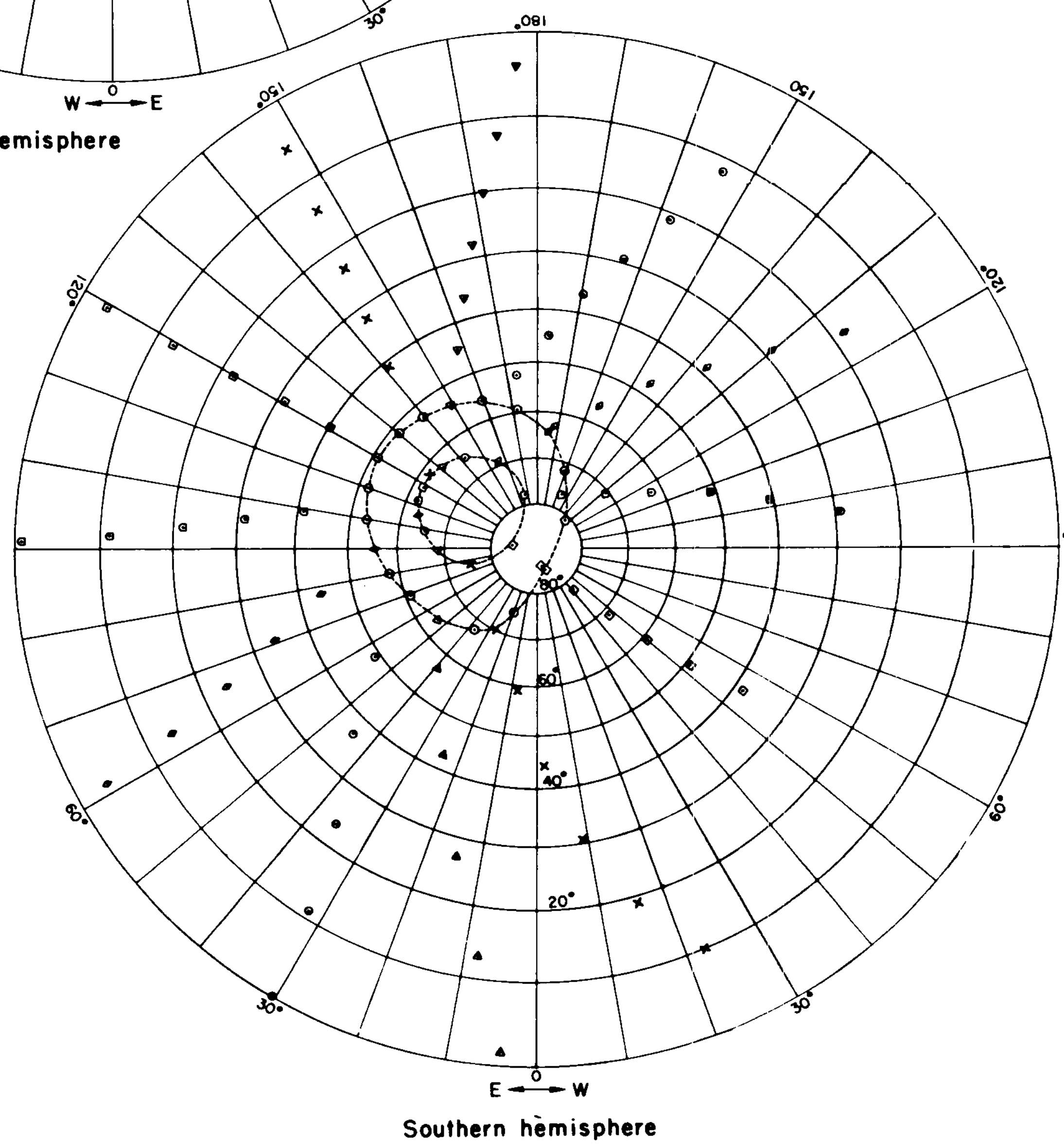
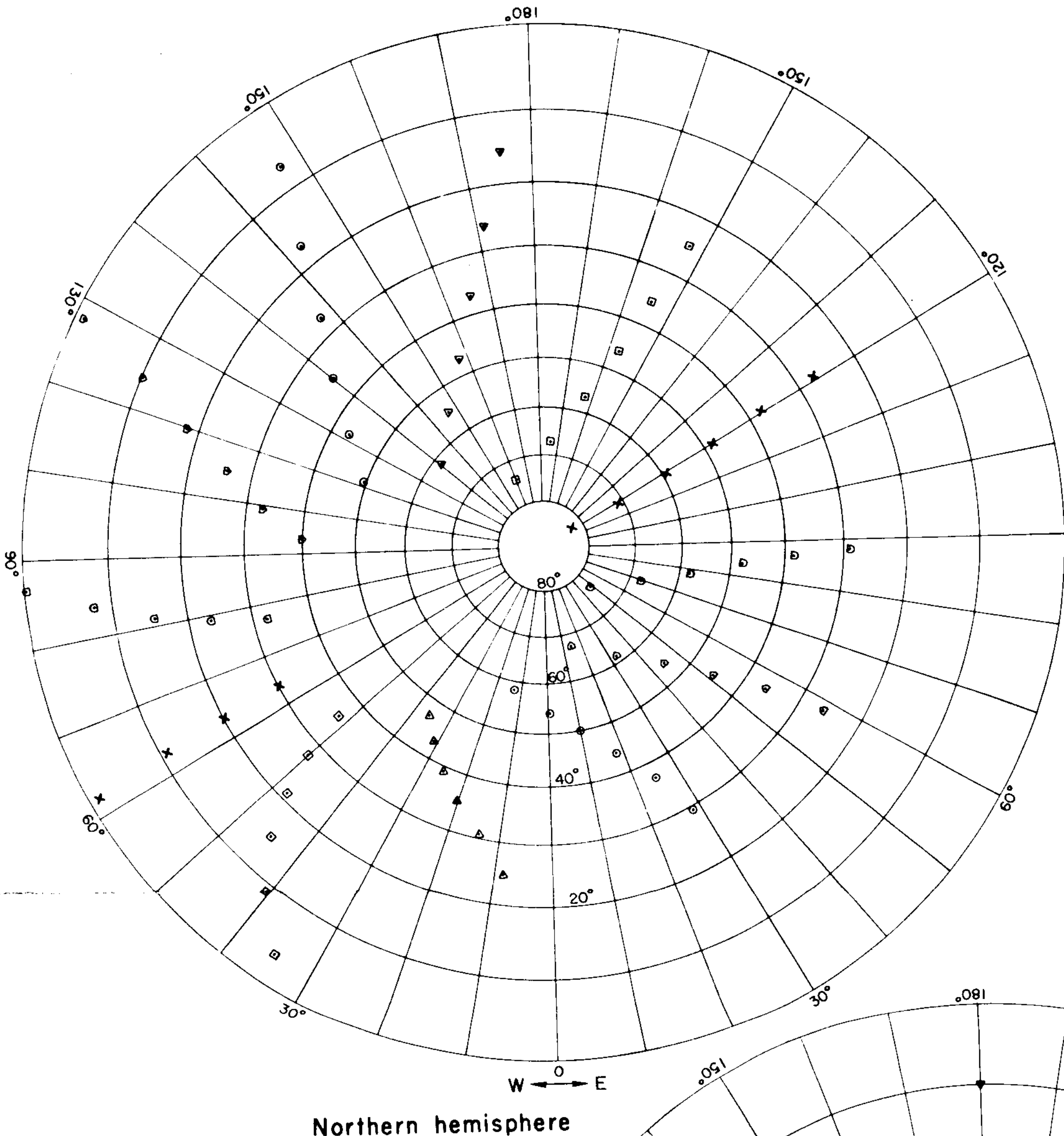


Fig. 11A Conjugate points derived from the analysis of Vestine and Sibley; southern hemisphere points conjugate with uniform grid of northern hemisphere points (auroral isochasms are shown)



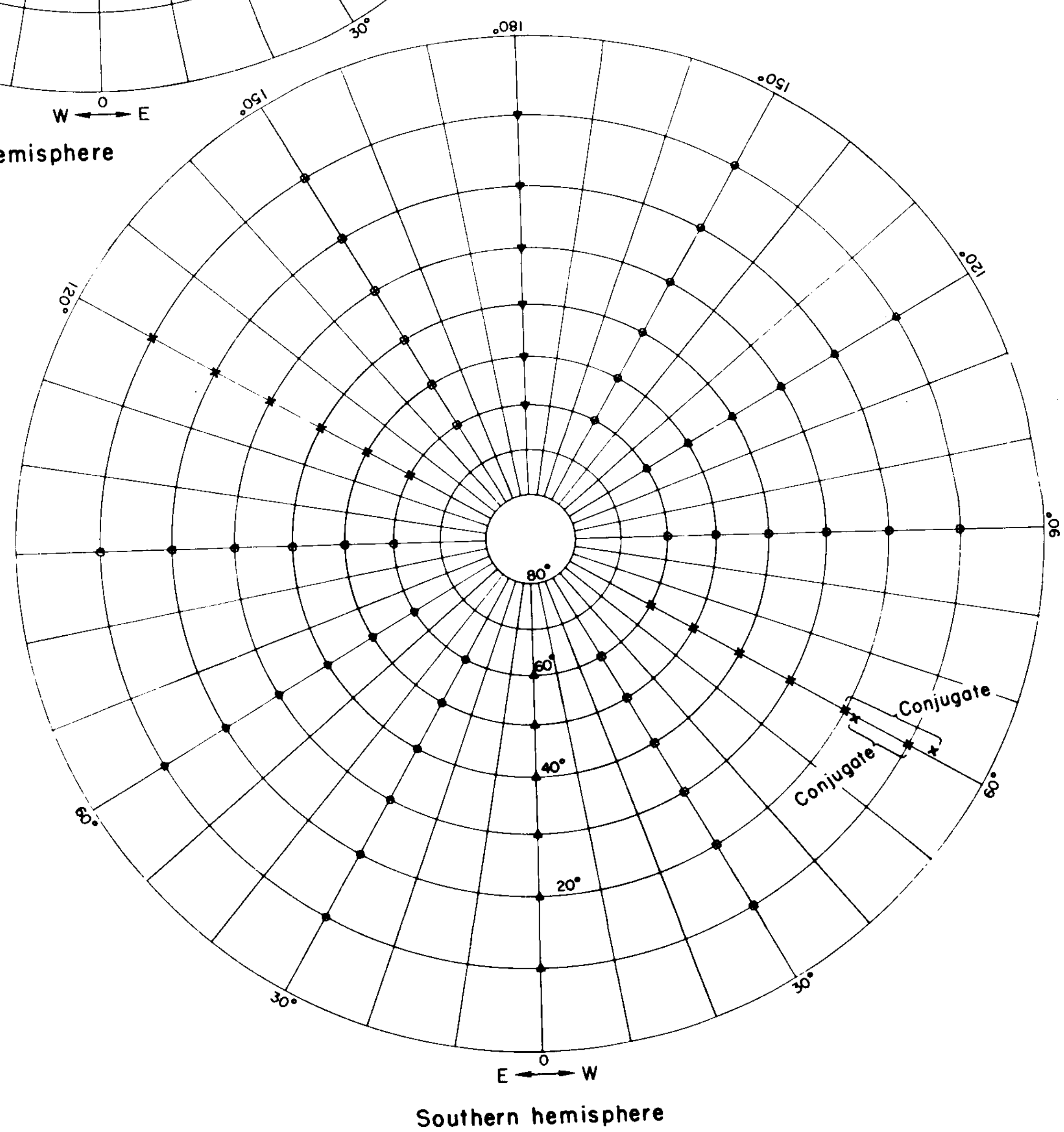


Fig. 11B Conjugate points derived from the analysis of Vestine and Sibley; northern hemisphere points conjugate with uniform grid of southern hemisphere points

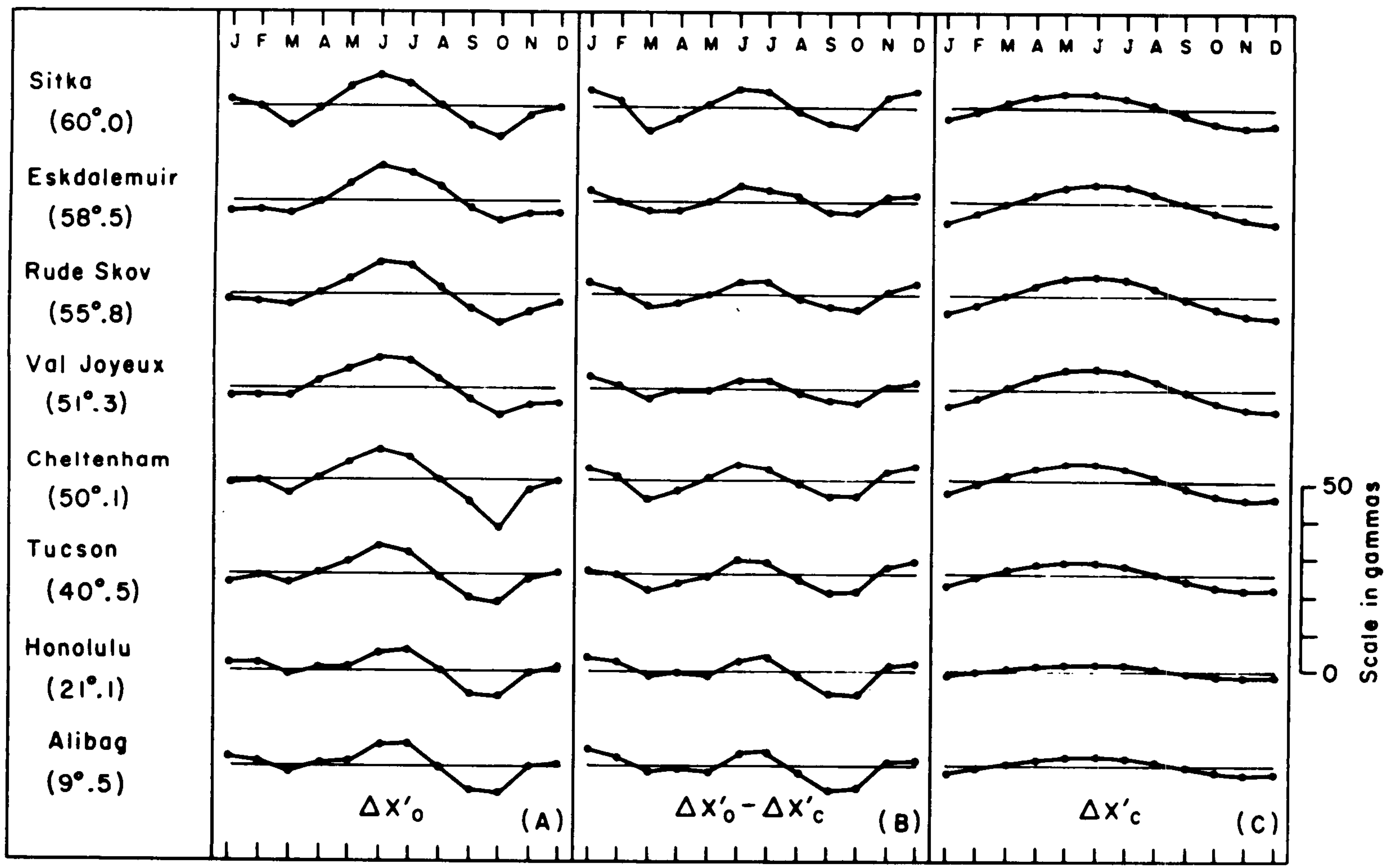


Fig. 12 Average annual variation of X'-component, 1911 to 1935

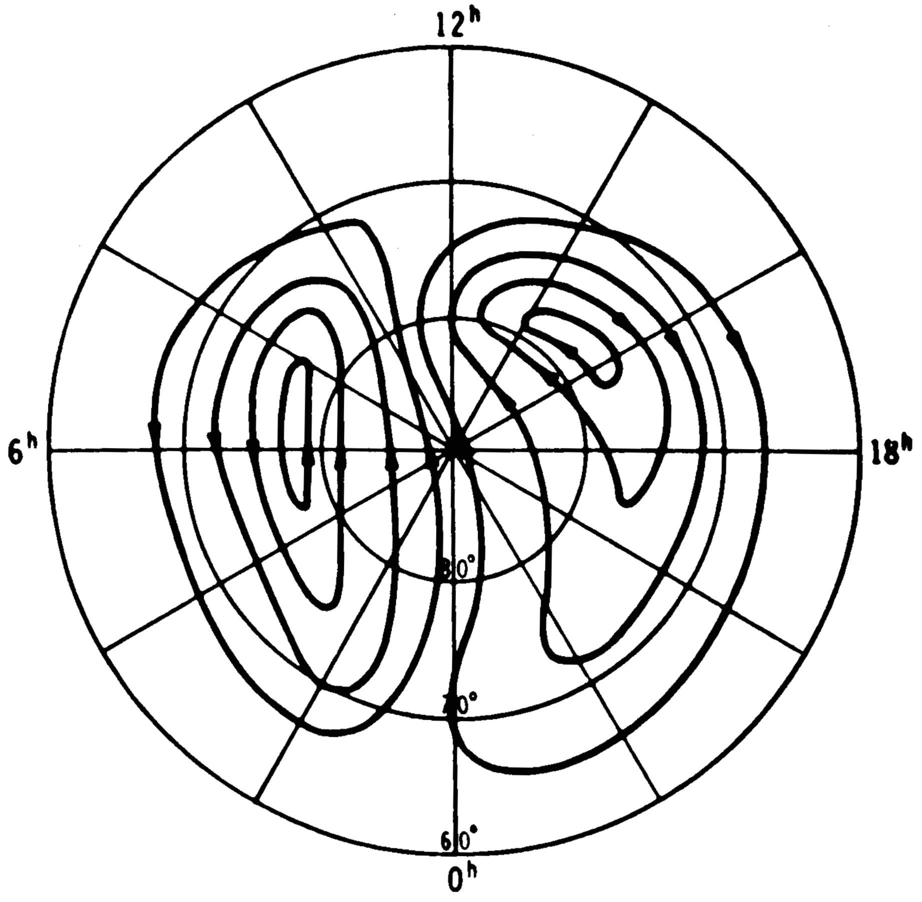


Fig. 13 The additional sunlit polar cap current pattern. Sq(SP) (Electric current between adjacent lines is 2×10^4 amp)
(after Nagata)

1920

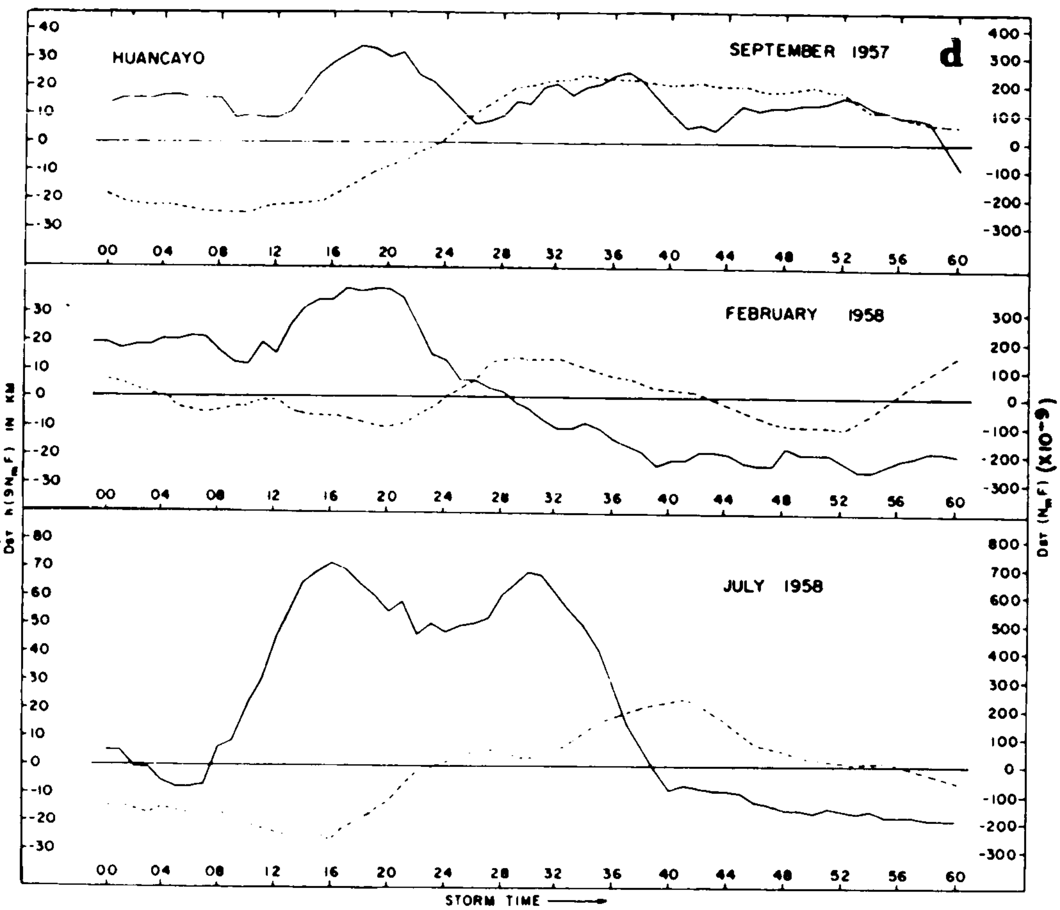


Fig. 14 Dst variations of the maximum electron density of the f region (broken line) and the $h(0.9N_mF)$ during storms (after Somayajulu)

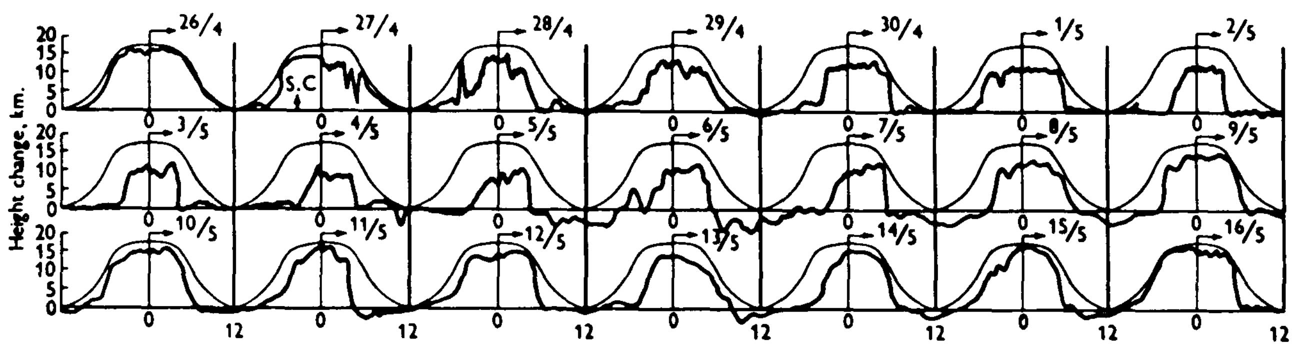


Fig. 15 Variations in phase height of waves of frequency 16 kc/sec. Observed at Cambridge, 1956 (after Ratcliffe and Weekes)

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